VOLCANIC INTRUSIONS ON MARS: HEAT SOURCES TO MAINTAIN VIABLE ECOSYSTEMS?

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Structure of volcanoes.

Centers of basaltic activity located over mantle hotspots on both Earth and Mars produce the same basic pattern of a shallow magma reservoir (commonly marked by a collapse crater or caldera) located beneath the summit of a shield volcano (Mouginis-Mark, Wilson & Zuber, 1992). Near-vertically oriented dikes (pressurized magma-filled cracks) propagate mainly laterally away from the reservoir whenever it becomes excessively over-pressured by the arrival of batches of magma from the mantle beneath. These dikes either stall within the body of the volcano as intrusions or, if they grow vertically by a great enough distance, erupt at the surface to feed lava flows or explosive eruptions. The growth of many shield volcanoes is influenced by pre-existing regional stresses in such a way as to concentrate dike injection into relatively narrow zones — rift zones — oriented radial to the summit. Intrusions outnumber surface eruptions by a factor of several to one.

The main difference between terrestrial and martian volcanoes is caused by the lower acceleration due to gravity on Mars (Wilson & Parfitt, 1990; Wilson & Head, 1994). The interplay between stresses arising due to gravity and stresses linked to the elastic properties of rocks causes all martian magma reservoirs to be centered at greater depths and to be larger in both horizontal and vertical dimensions (Parfitt, Wilson & Head, 1993; Head & Wilson, 1994). The greater magma volumes housed by these reservoirs cause laterally propagating rift-zone dikes to be both horizontally and vertically more extensive and also wider (i.e. thicker) than those on Earth: Table 1 shows typical values of vertical height and width.

Any shield volcano grows as a stack of interleaved, sub-horizontal layers of volcanic ash from explosive eruptions and vesicular lava from effusive eruptions cut, at any given level within the pile, by the near-vertical dikes feeding later eruptions. Once the products of any one eruption have cooled, the pore spaces between ash particles and the vesicles within lava flows form natural locations for the near-surface accumulation of water ice and solid carbon dioxide. The very low atmospheric pressure on Mars causes more exsolution of magmatic volatiles (mainly water and CO_2) than on Earth; this means that explosive eruptions were more common on Mars than Earth (Wilson & Head, 1983) and that lava flows were more vesicular, both factors enhancing the trapping of volatiles from the atmosphere.

Thermal consequences of dike injection.

There are several ways in which the intrusion of new dikes influences the thermal structure of the old eruptives into which they are intruded and thus the state (solid or liquid) of the H_2O trapped in these rocks. If a dike is intruded into a region which has seen no activity for a long time, then close to the new dike the heat pulse will raise the temperature first above the melting point of H_2O and then above the boiling point; further away only the melting point will be exceeded. The time scale t_1 over which such a heating event lasts is of order 5 (w^2/κ) where w is the dike width and κ is the thermal diffusivity of the magma; for w = 5 m and $\kappa = 10^{-6}$ m^2 s^{-1}, $\tau_1 \approx 4$ years. The lateral width of the region affected is ~6w = 30 m.

Where successive dikes are intruded near to one another in a rift zone, part of the region between any two dikes can stay at a temperature such that H_2O is a liquid for a much longer time provided that new dikes arrive on a time scale comparable with τ_1. We can estimate the time interval between intrusions by noting that to assemble the typical volume of a large martian volcano (~10^6 km^3 for the Tharsis shields) in 1 Ga (i.e. 3 x 10^{16} s) by randomly intruding dikes 50 km in horizontal extent, 13 km in vertical extent and 6 m thick (c.f. Table 1) implies that the time between events is ~4000 years. However, if these dikes are confined to a rift zone, the time interval between events is less. The Hawaiian shield volcanoes on Earth have active rift zones which at any one time are only a few hundred meters wide and occupy only about 1/200 of the horizontal cross-sectional area of the volcano. Preliminary estimates from Viking Orbiter images suggest that the ratio is similar for Mars, reducing the mean interval between nearby intrusions to 4000/200 = 20 years. This value is close enough to the 4 years found earlier to suggest that significant local "warm zones" can exist down to depths of several kilometers in volcanic rift zones.

Regional heat flow effects.

An alternative assessment takes account of the fact that, over the whole extent of a rift zone, the net effect of the intrusions is to increase the regional heat flow and locally raise the geotherm toward the surface on the time scale over which the rift zone remains the preferred site of activity. The total amount of heat, H, available from cooling the magma required to build a shield volcano of volume V is H = (V ρ S $\Delta\theta$) where r is the mean density of the edifice, S is the specific heat of the magma and $\Delta\theta$ is the temperature interval through which the magma cools. Substituting typical values of V ~10^6 km^3, r ~3000 kg/m^3, S ~1000 J kg^{-1} K^{-1} and Dq ~1000 K, we find H ~ 3 x 10^{24} J. The time scale for release of this heat is, as before, ~1 Ga = 3 x 10^{16} s and the total surface area of the volcano with diameter 500 km is ~8 x 10^{11} m^2 implying a mean heat flux Q_V of ~1.3 x 10^{-4} W m^{-2}. If the fractional area of rift zones at any one time is again taken as 1/200 of the surface area of the volcano, the local heat flux is more like $Q_V = 2.5 \times 10^{-2}$ W m^{-2}. This is comparable to the present day planetary average geothermal heat flux Q_g estimated at between 3 and 4 x 10^{-2} W m^{-2} (Squyres et al., 1992).

We are mainly concerned with the influence of volcanic heat sources at some time part-way through martian geological history when the geothermal heat flux was higher than the current value by a factor of, say, 2 or 3, i.e. ~8 x 10^{-2} W m^{-2}; the volcanic flux would then have represented a 30% increase in the heat flow. Estimates of the depth to the base of the cryosphere based on the current geothermal heat flow range from about 2 km near the equator to about 5 km near the poles. With the higher earlier flux these depths would have been ~800 m and ~2000 m, respectively and the 30% increase in heat flow would have changed them to ~615 and ~1540 m, respectively. Thus, the vertical extent of the zone within which H_2O could be present as liquid water could have been extended by at least 200 to 400 m, depending on the latitude.

Summary.

The above calculations suggest that the local volcanic heat sources inevitably present in the rift zones on the flanks of large martian volcanoes could have very significantly extended the sizes of regions within which water could persist as a liquid for time periods of at least tens and probably hundreds of millions of years, the latter intervals being long enough, by analogy with what happened on the Earth, for significant biological development (McKay and Stoker, 1989). It is possible that the ultimate limitation on the lifetime of such favored regions is not so much the availability of heat but rather the need to prevent water from leaving the regions too rapidly as a result of the imposed thermal gradient (McKay et al., 1992) or to re-supply water from deeper levels in the hydrothermal system of the volcano to compensate for that lost. We are presently investigating geological environments on Mars where such conditions might have persisted.

Table 1. Widths (w) and vertical heights (h) of dikes centered at neutral buoyancy levels in the rift zones of volcanoes on Earth and Mars for a range of plausible driving pressures, P_0, defined as the amounts by which the pressure in the dike at its mid-point exceeds the external compressive stress.

	Earth		Mars	
P_0/MPa	h/km	w/m	h/km	w/m
5	0.95	0.45	4.8	1.4
10	4.7	2.3	12.9	5.7
20	9.7	8.7	28.0	22.6

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